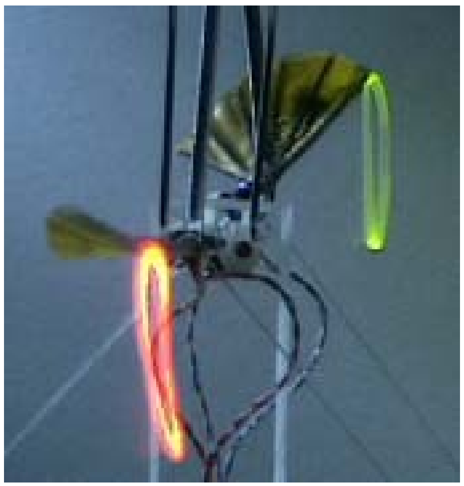
Dynamic Modeling and Controls Research for Biologically Inspired Micro Aerial Vehicles



NASA Langley Research Center

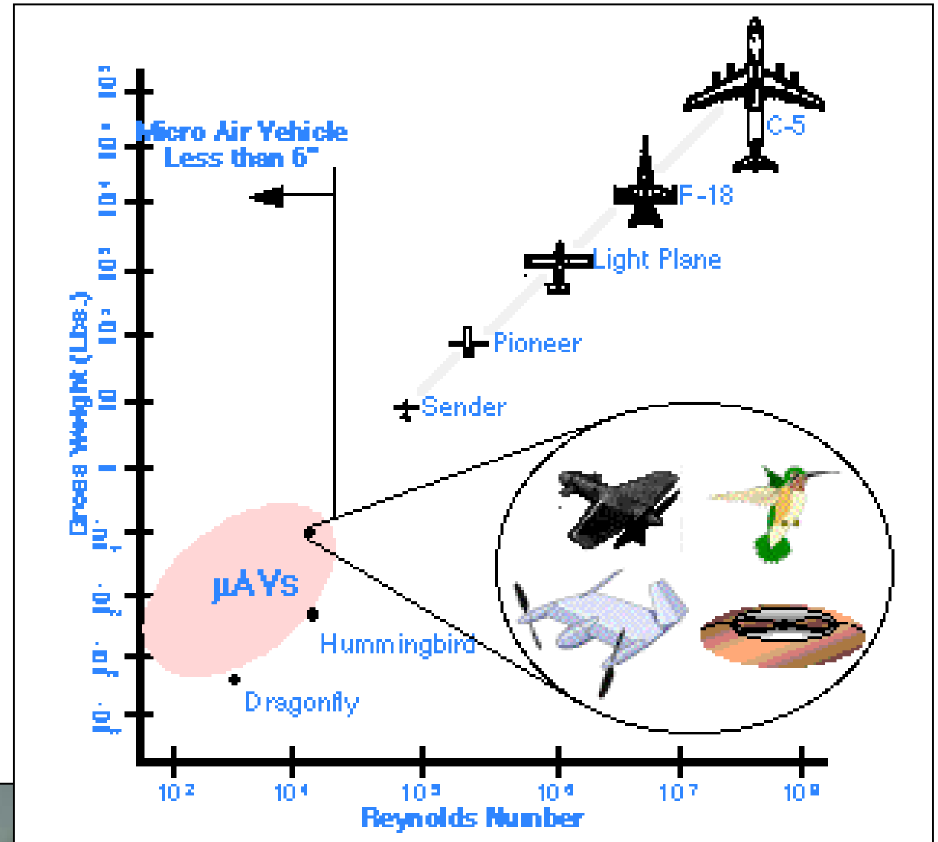
David L. Raney, Martin R. Waszak

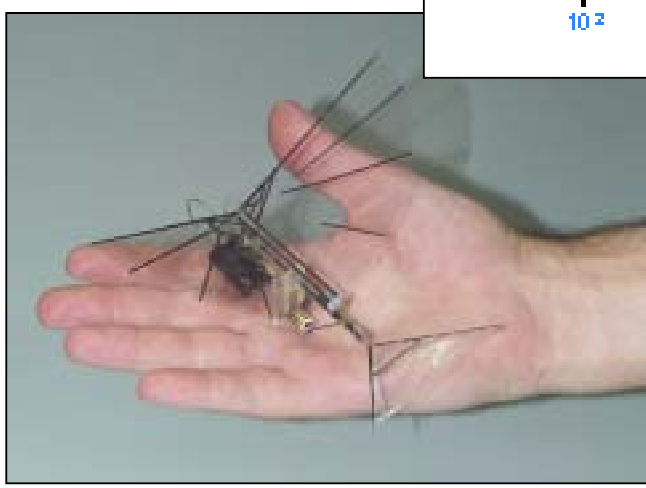
Dynamics and Control Branch

d.l.raney@larc.nasa.gov, m.r.waszak@larc.nasa.gov

Ref: AIAA 2003-5345, 2002-4875, 2001-4005

What are Micro Aerial Vehicles?



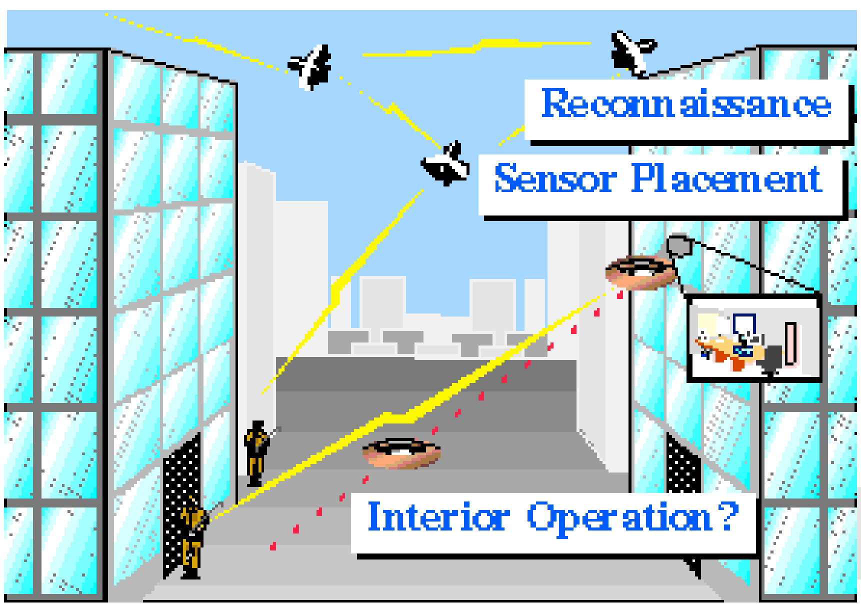


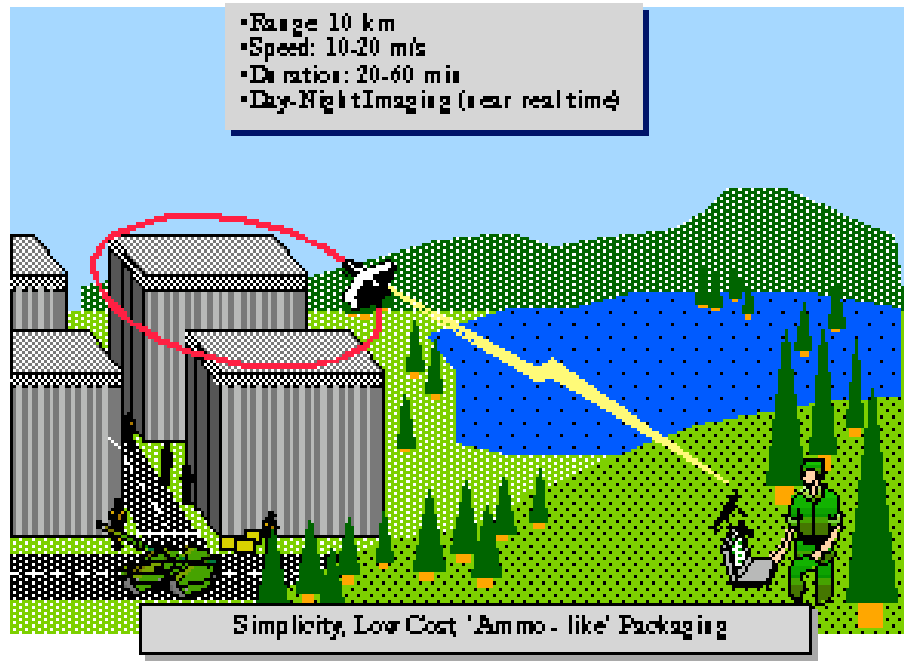
The Promise of MAVs

An emerging sector of aerospace industry with potential to become a consumer product

Rapidly Deployable "Eye in the Sky"

- traffic/news/sports
- inspection
- reconnaissance





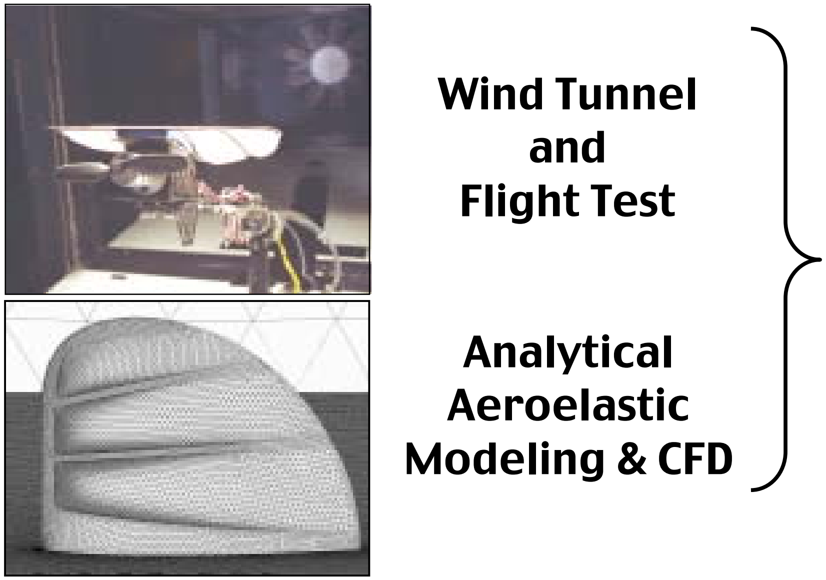
Delivery/Transmission/Relay

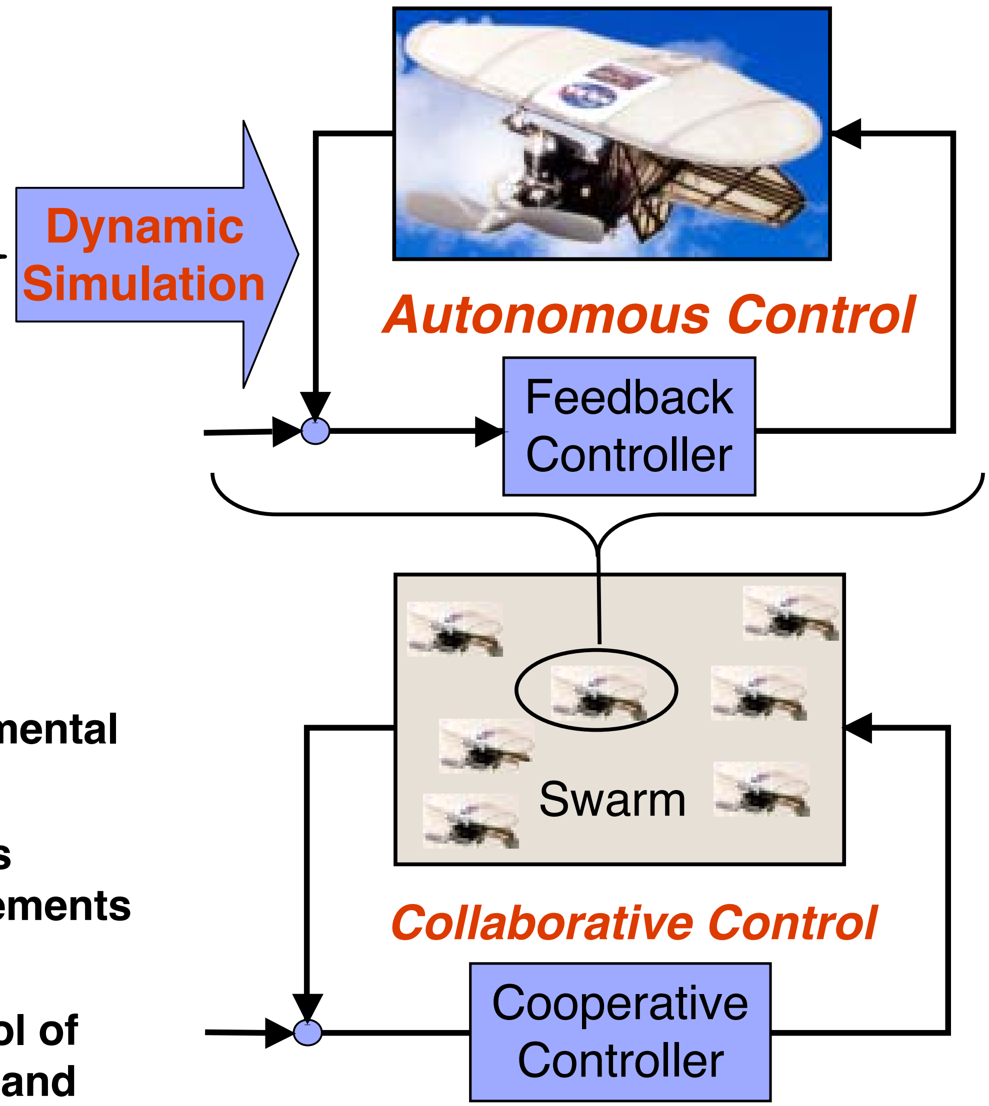
- micro payloads
- communications

Remote Distributed Sensing

- agriculture/forestry
- atmosphere/weather
- search & rescue

Approach to Fixed-Wing MAV Research





Leverage an existing vehicle concept

Generate and use analytical and experimental databases to create dynamic simulation

Develop autonomous control algorithms
- **Identify sensor and actuator requirements**
- **Flight test control algorithms**

Research swarming / cooperative control of collaborative systems using simulation and flight test

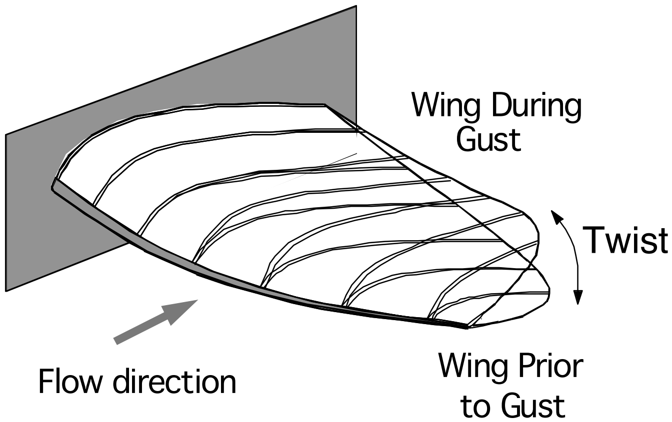
University of Florida MAV

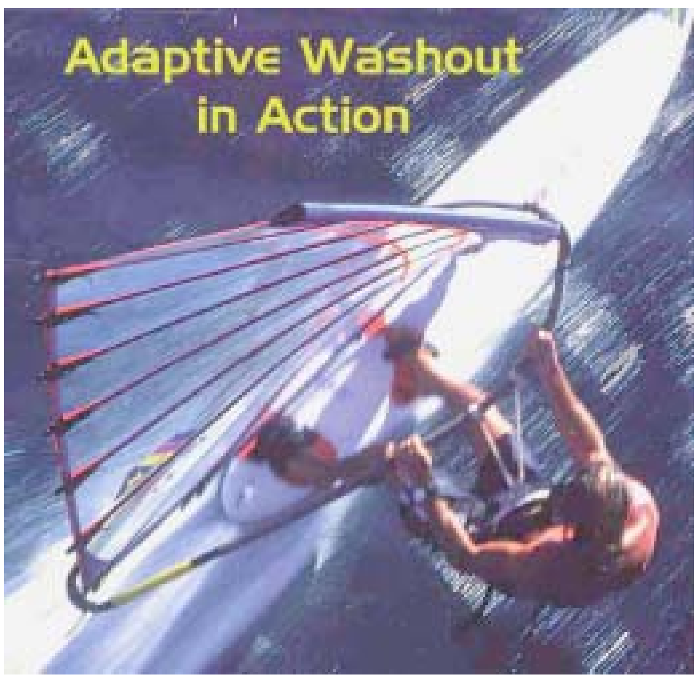
poc: Peter Ifju, ifju@ufl.edu

Maximum Dimension	**6 inches**
Empty Weight	**55 grams**
Span	**6 inches**
Wing Area	**20 inches^2**
Mean Chord	**3.3 inches**
Cruise Speed	**10 - 30 mph**
Payload Weight	**~20 grams**

Flexible Latex & Graphite Epoxy Wing

Adaptive Washout

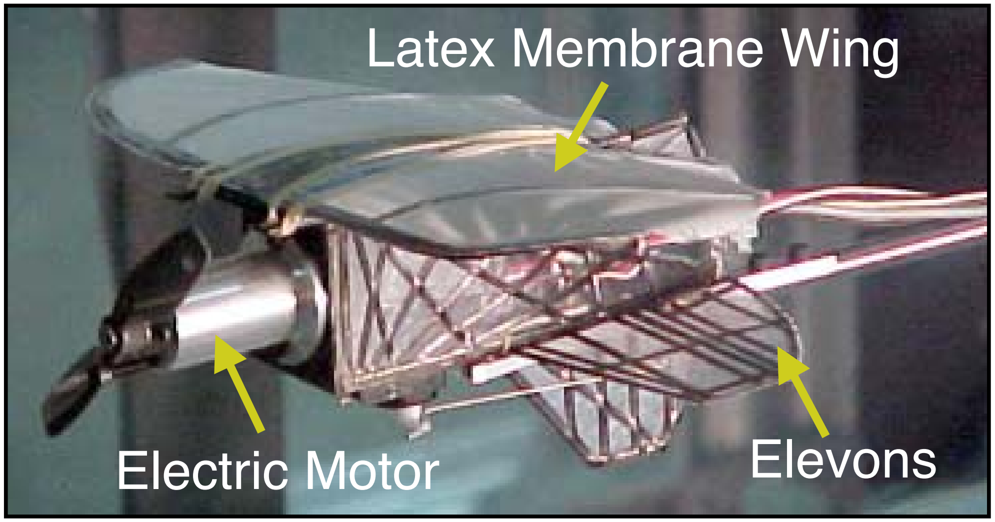




Response to periodic axial velocity perturbations.

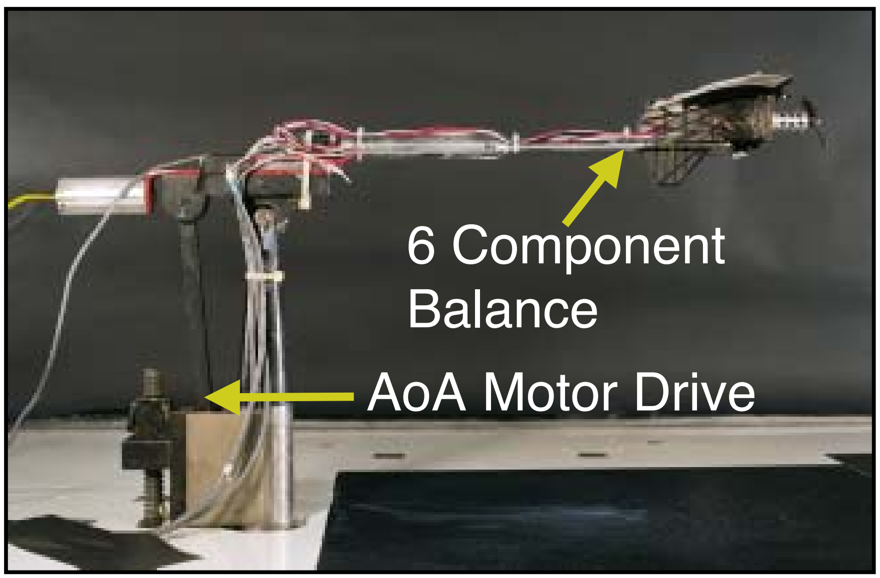
"Chopper" (U of F Wind Tunnel)

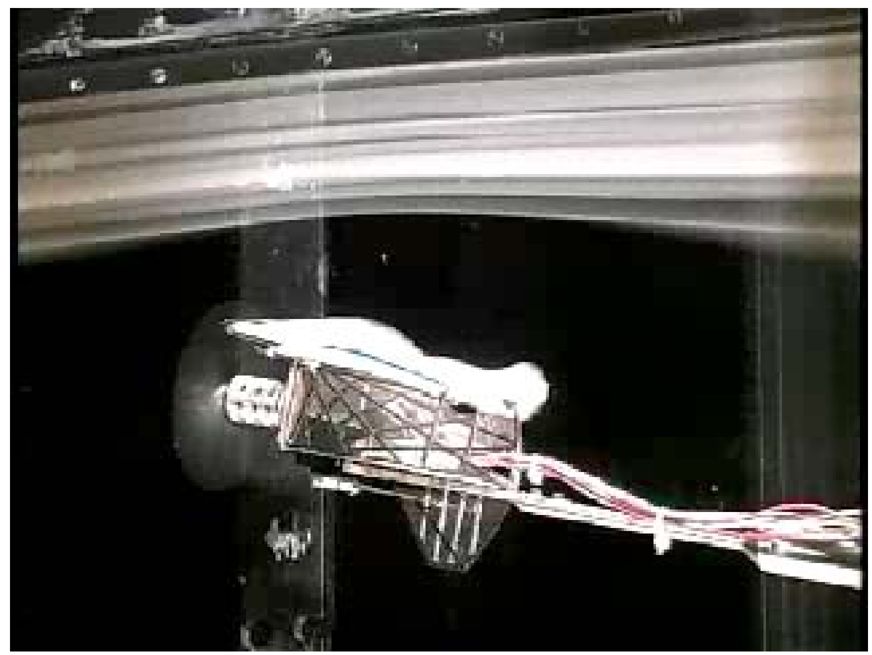
BART Wind Tunnel Test Configuration



Stability and Control Forces
& Moments
Flow Visualization
PMI for Wing Deformation
Wing Structure Variations

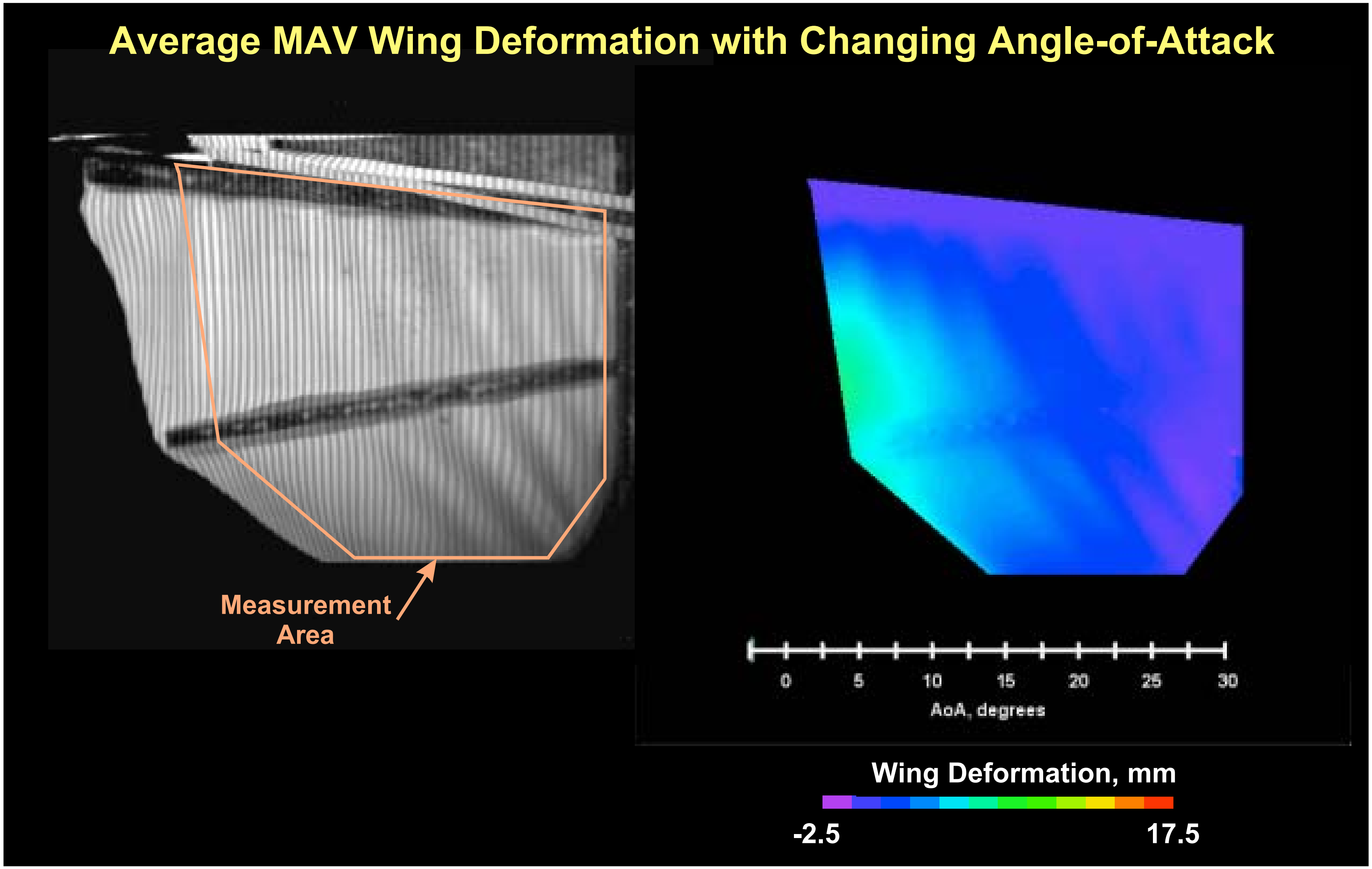
Conditions:
q = 1.6 psf (25 mph)
p = 12V (~18000 rpm)
α –5 to 45 degrees





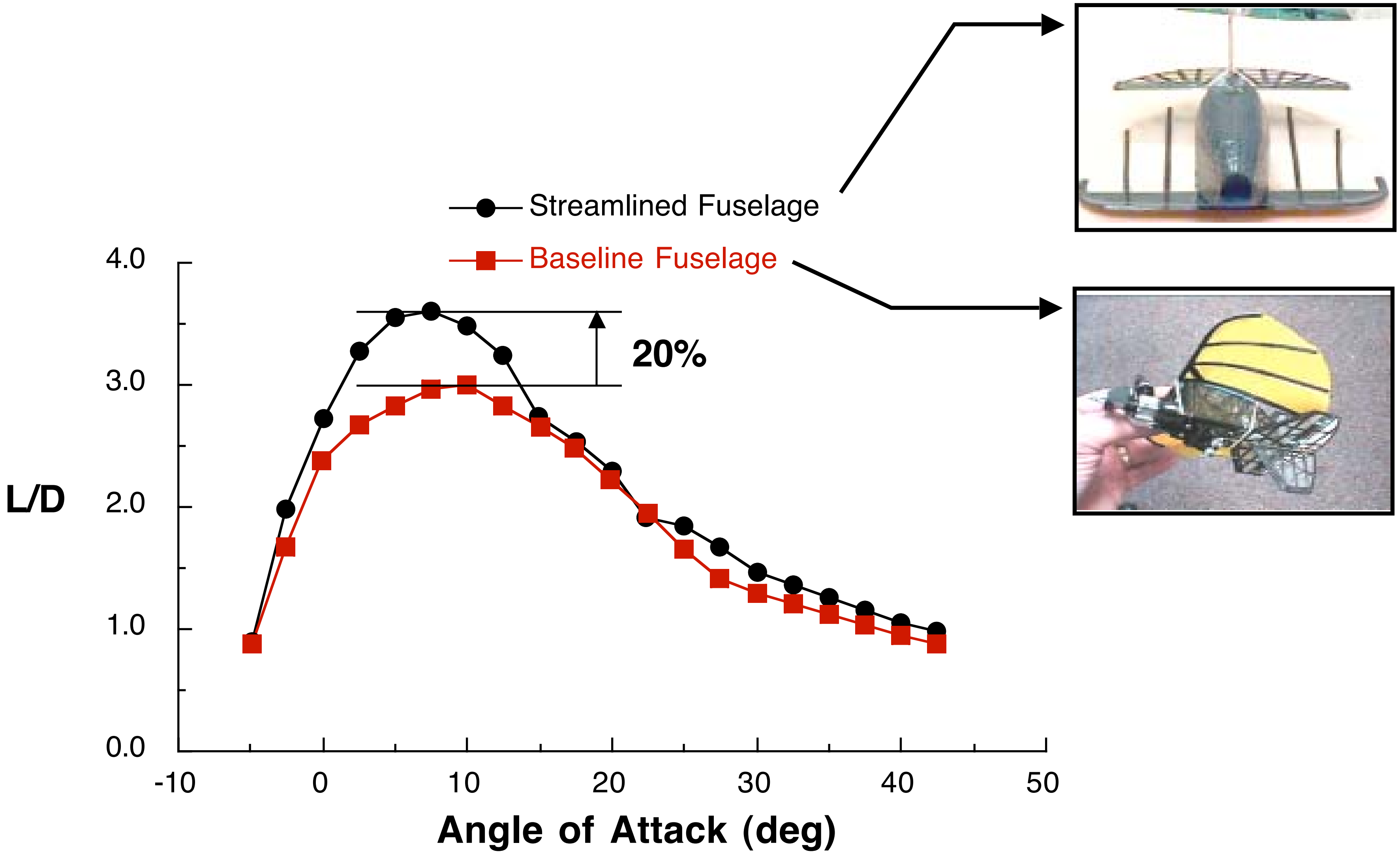
Measuring Wing Shape

poc: Gary Fleming, g.a.fleming@larc.nasa.gov

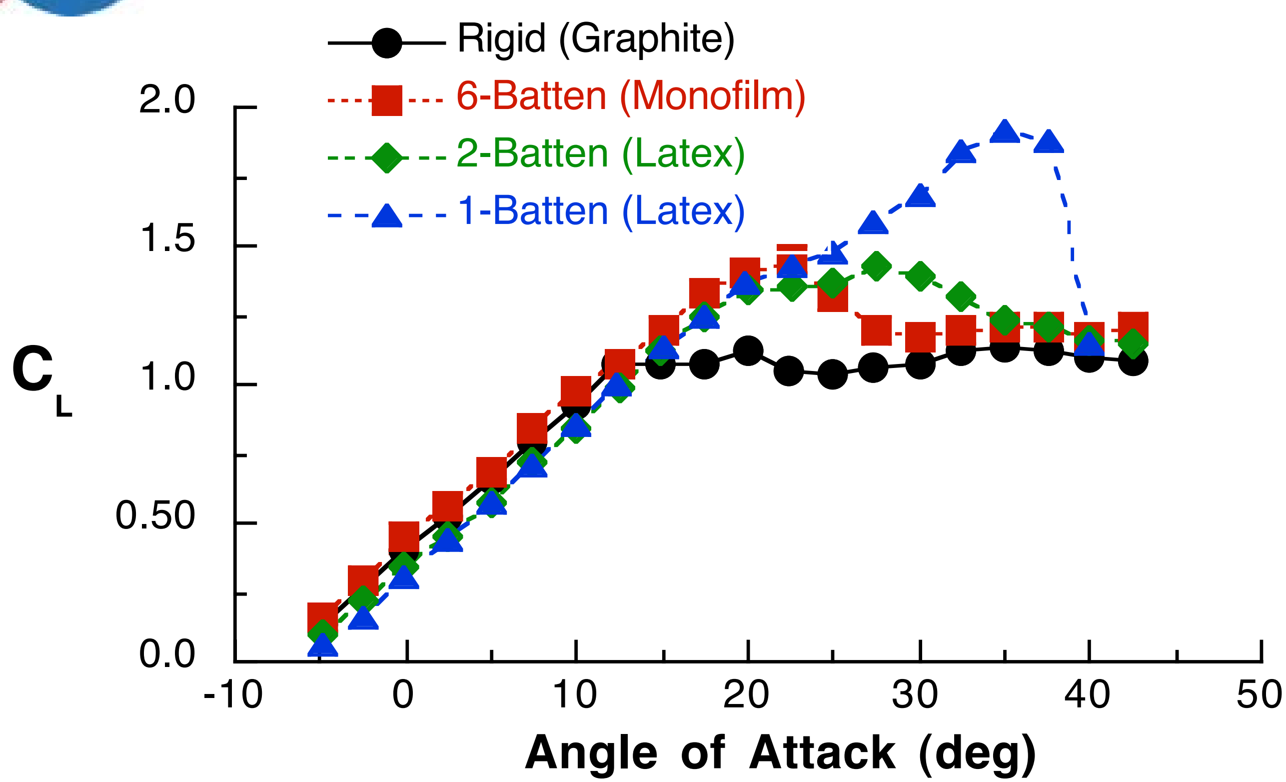


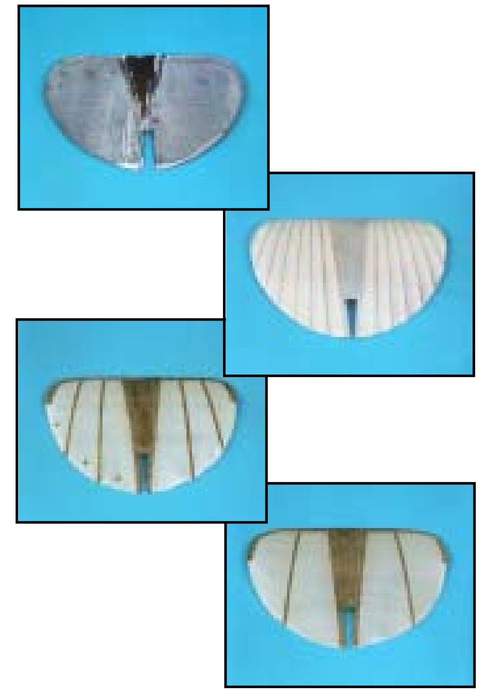
Streamlined Fuselage Effect

(q=1.6 psf, power off, 6-batten wing)



Static Aeroelastic Effects (q=1.6 psf, power off)





- **Similar lift curve slopes**

  comparable to other low Reynolds number wings with similar aspect ratio

- **Significant increases in stall angle with increased flexibility**

  stall angles comparable to other low Reynolds number wings with much lower aspect ratio

Stability and Control Properties

(q=1.6 psf, trim power, 2-batten wing)

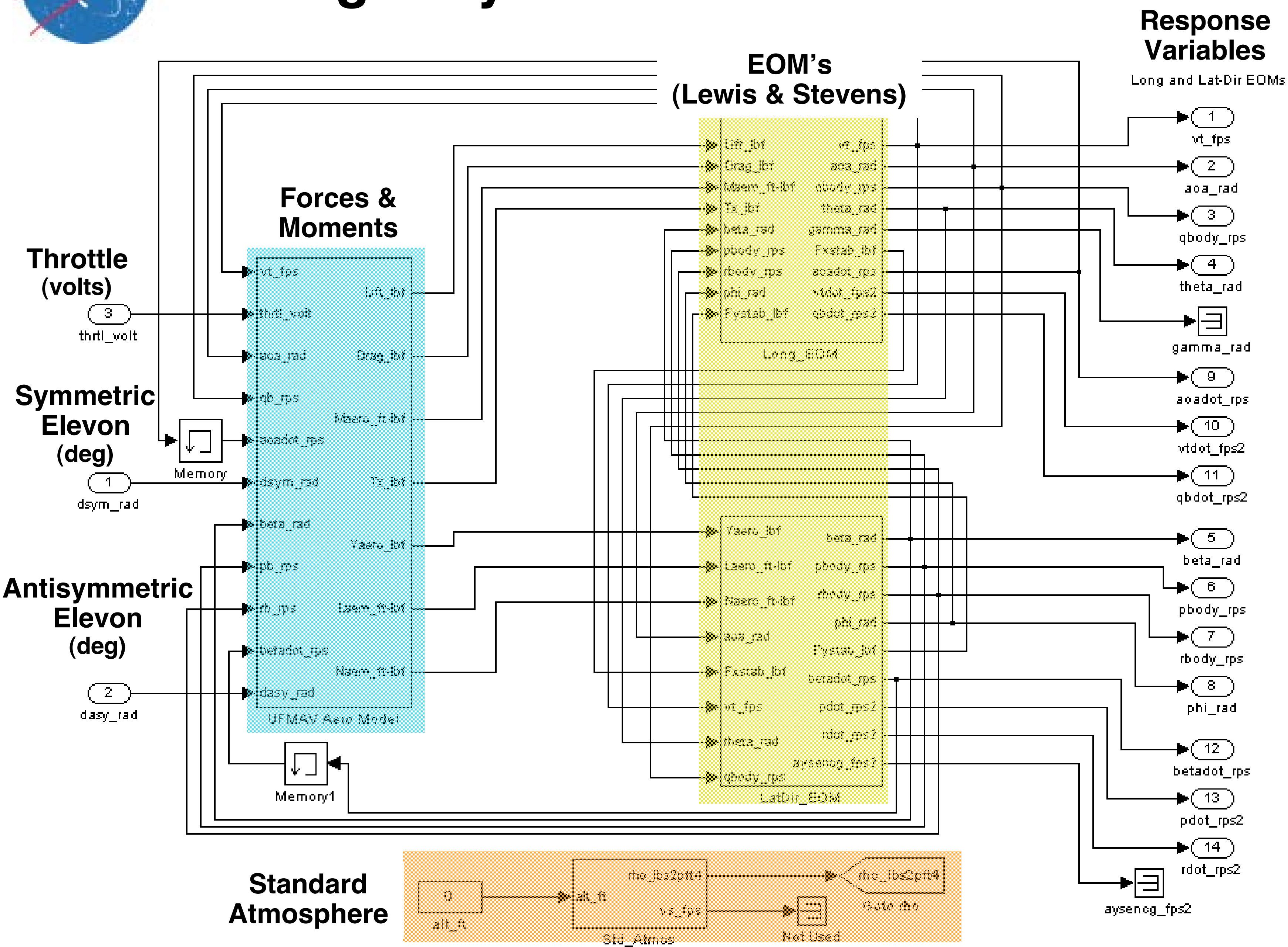
- Static Stability
  - Pitch Stability $C_{m_\alpha} = -0.6$
  - Static Margin $SM \cong \dfrac{C_{m_\alpha}}{C_{L_\alpha}} = 0.15$
  - Directional Stability $C_{n_\beta} = 0.5$
  - Dihedral Effect $C_{l_\beta} = -0.7$

statically stable in all axes

static derivatives somewhat larger than typical piloted aircraft

- Controllability
  - Symmetric Elevon $\left.\begin{array}{l} C_{L_\delta} = 0.7 \\ C_{m_\delta} = -0.4 \end{array}\right\} \dfrac{C_{L_\delta}}{C_{m_\delta}} = -1.75$ **characteristic of flying wing**
  - Antisymmetric Elevon $C_{Y_\delta} = -0.10$, $C_{l_\delta} = 0.08$, $C_{n_\delta} = 0.06$

Flight Dynamic Simulation Model



Simulation/ Vehicle Characteristics

Dynamic Pressure (psf)	Phugoid Mode		Short Period Mode	
	freq. (rad/sec)	damping ratio	freq. (rad/sec)	damping ratio
1.0	0.85	0.44	23.3	0.13
1.6	0.65	0.35	30.2	0.12
2.0	0.67	-0.56	32.6	0.12

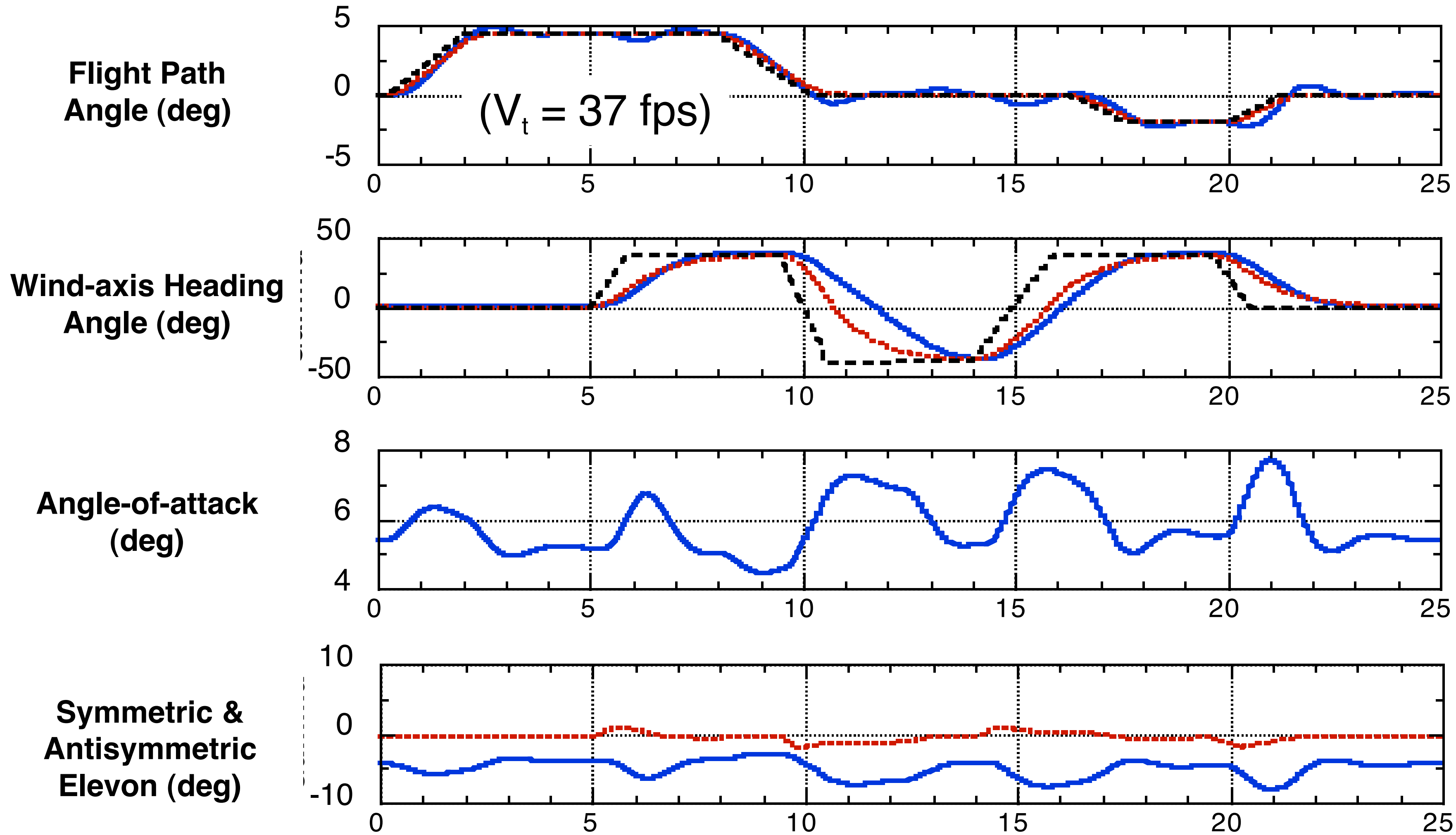
- Stable but lightly damped short period mode
- Phugoid unstable at higher speeds

- All lat-dir modes stable
- Lightly damped dutch roll mode

Dynamic Pressure (psf)	Spiral Mode	Roll Mode	Dutch Roll Mode	
	e-value	e-value	freq. (rad/sec)	damping ratio
1.0	-1.04	-27.7	21.1	0.094
1.6	-1.04	-37.3	24.2	0.065
2.0	-1.02	-42.8	25.9	0.050

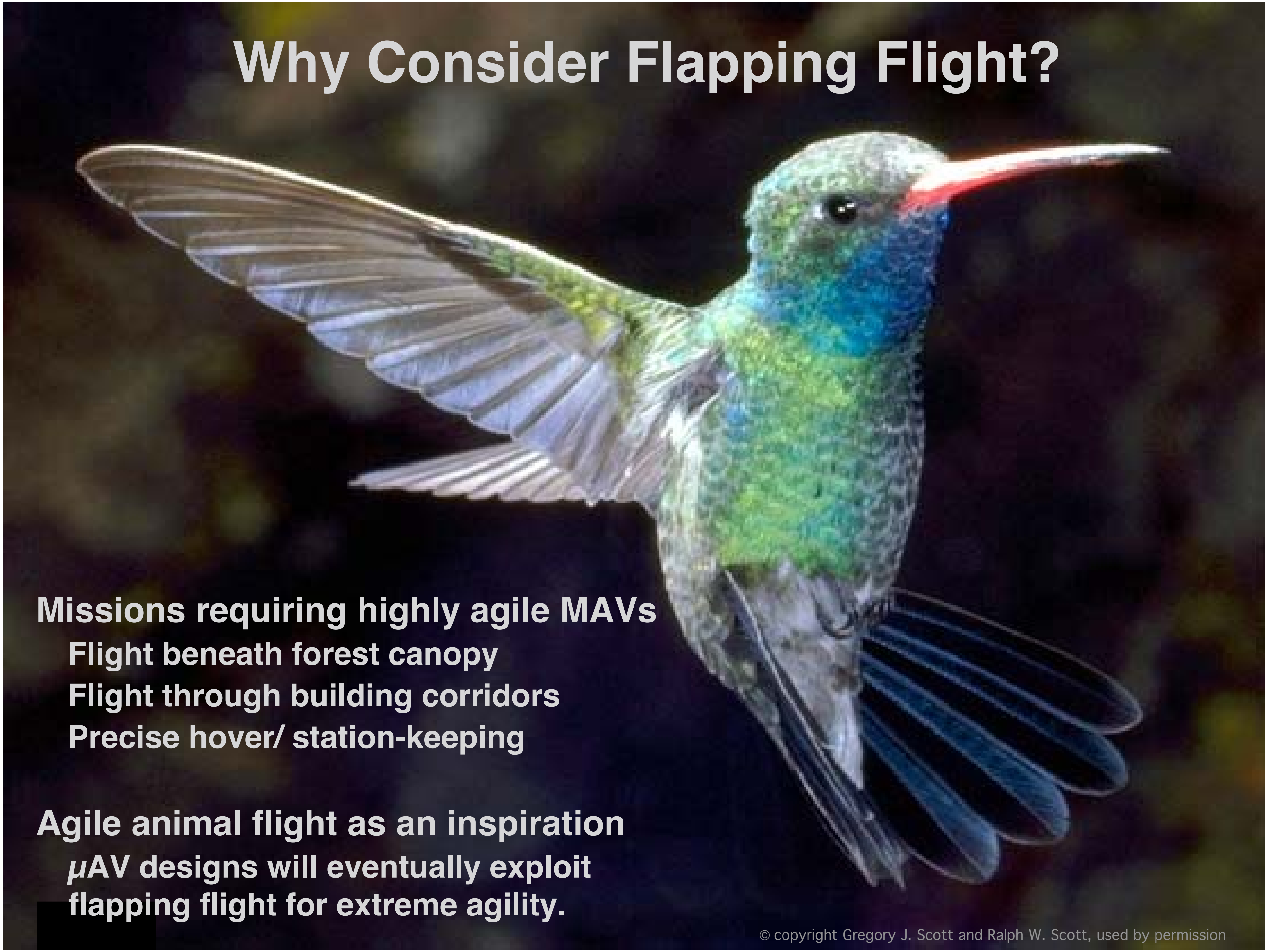
Dynamic Inversion Controller Performance

poc: John Davidson, j.b.davidson@larc.nasa.gov



√ **Test > Modeling/Simulation > Autonomous Single Vehicle >>**

next: Collaborative Multiple Vehicles


Why Consider Flapping Flight?
Missions requiring highly agile MAVs
Flight beneath forest canopy
Flight through building corridors
Precise hover/ station-keeping
Agile animal flight as an inspiration
μAV designs will eventually exploit
flapping flight for extreme agility.
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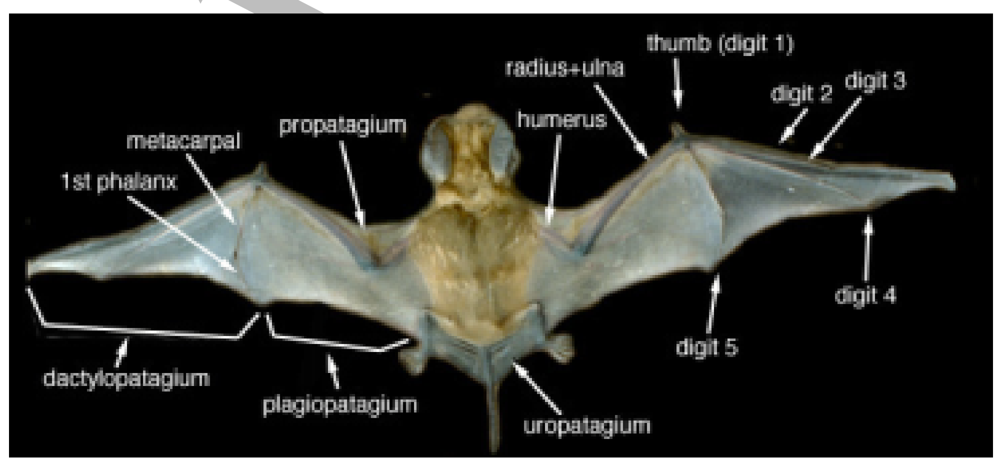
Bio-Inspired Principles from Diverse Examples of Flapping Flight

Flight modes
Wingbeat patterns
Wing design

Sensing

Structures



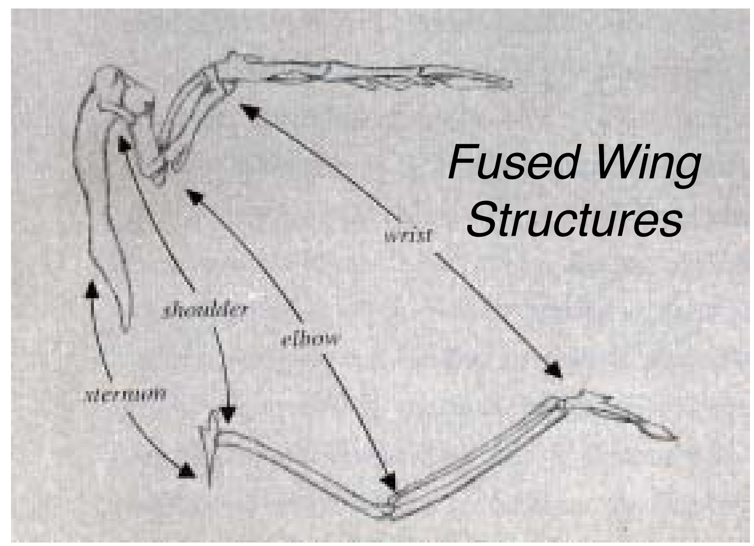
Tractable Flapping Wing Design

Many natural fliers generate lift through resonant excitation of an aeroelastically tailored structure:

Muscle tissue
•
Mode shape
•
Propulsive lift

The humming bird as a starting point:
- the right size
- the right capabilities
- *tractable* example

ref: Greenwalt, 1960

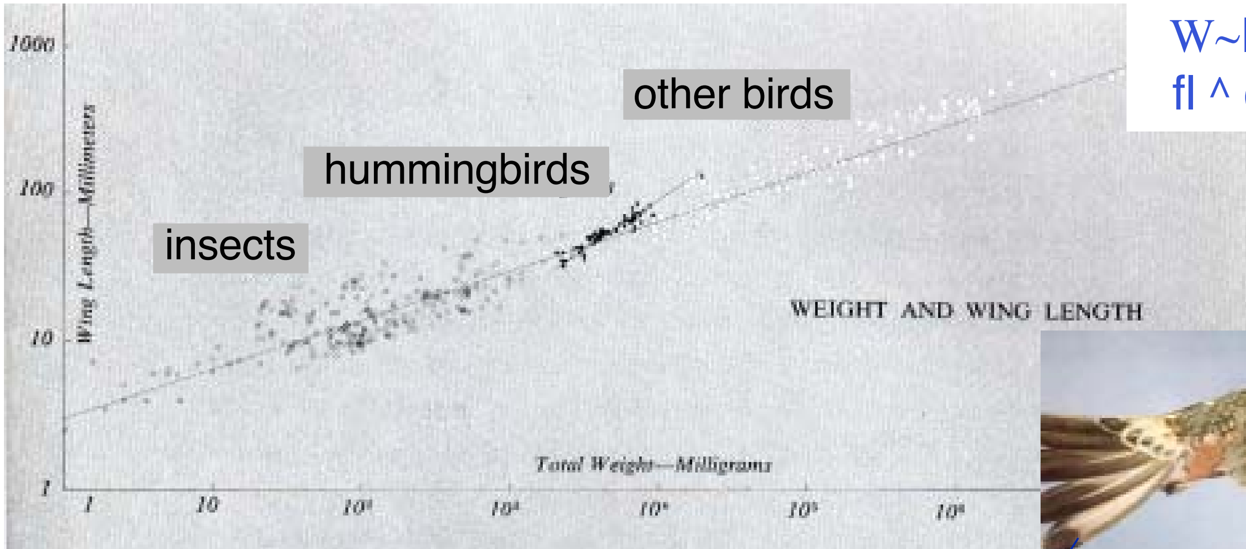


Where to Start?

Scaling relationships

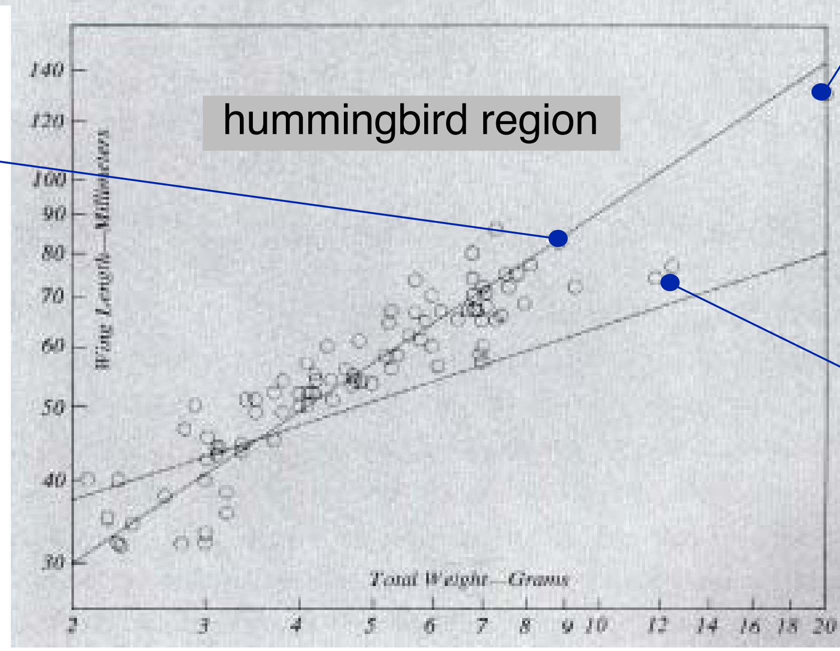
W~l ^(3/2)
fl ^ (1.25) = const.

Wing Length
vs.
Total Weight



Patagona gigas (Giant Andean)
Length of wing ~ 12 cm
Flapping frequency ~ 8 -10 Hz
Weight ~ 20 g

Lampornis clemenciae (Blue Throat)
Length of wing ~ 8.5 cm
Flapping frequency ~ 23 Hz
Weight ~ 8.4 g



ref: Greenwalt, 1960

MicroBat (Aerovironment)
Length of wing ~ 7.6 cm
Flapping frequency ~ 20 Hz
Weight ~ 12.5 g

Approach

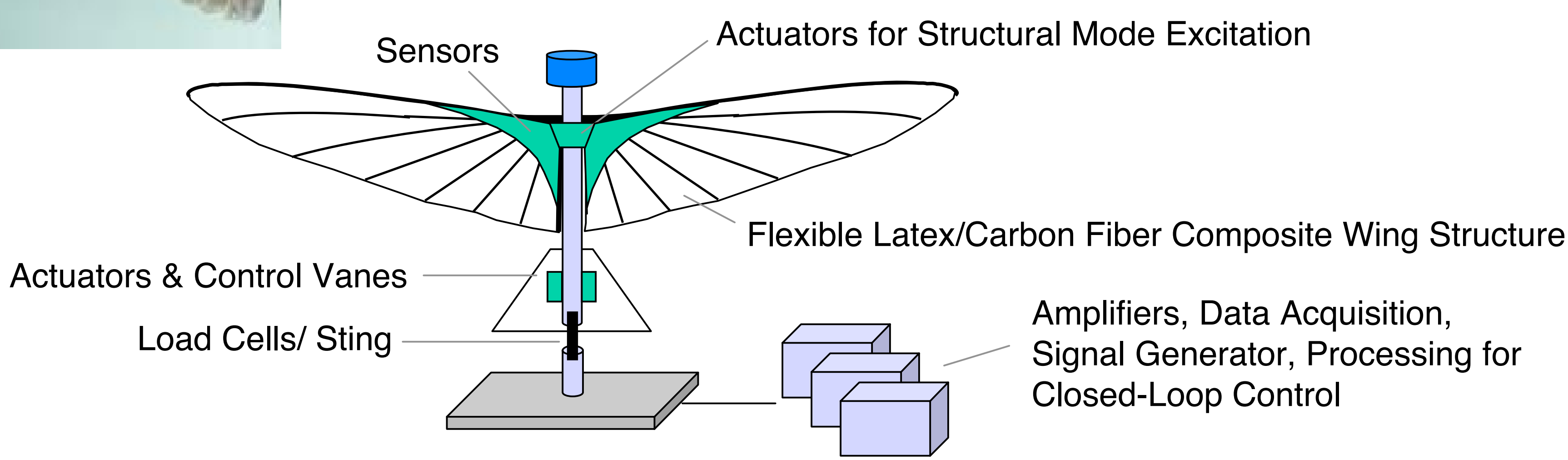
Apply UF MAV structure to bio-inspired wing layouts

Build series of vibratory testbeds & simulation models

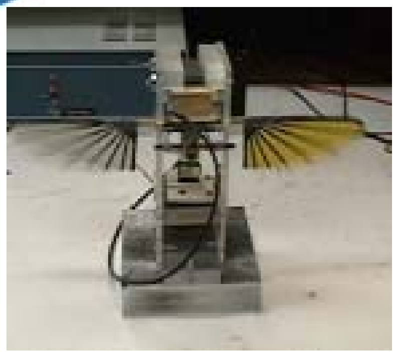
Excite aeroelastic/structural dynamic modes to produce large-amplitude resonant flapping behavior

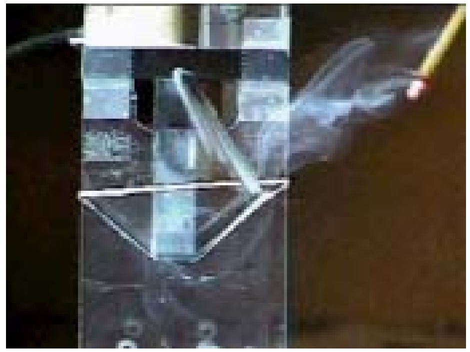
- Investigate parametric variations of wing layup
- Develop/ refine mechanization concepts
- Achieve control of resonant wingbeat kinematics

Hardware-in-the-loop dynamic simulation & control

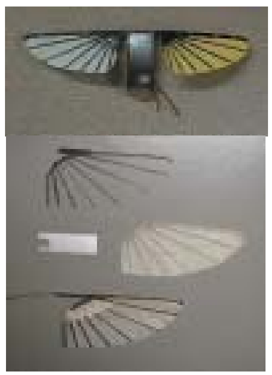


Progression of Resonant Flapping Testbeds

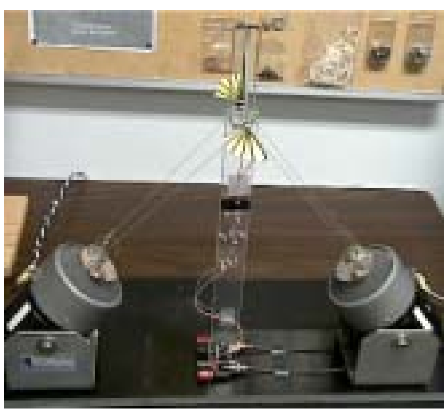


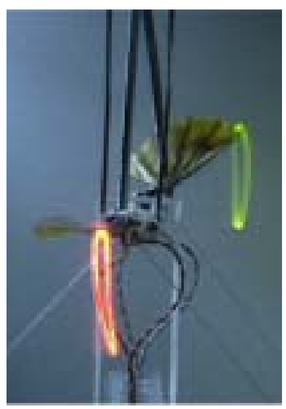


EM Vibration Inducer **('99-'00)**
- Basic proof-of-concept
- OL frequency sweeps/ resonant frequencies
- Structures/ Materials



Piezo Ceramic **('00-'02)**
- Strain rate feedback/ resonant tuner
- Vacuum chamber tests
- Parametrics & flow vis

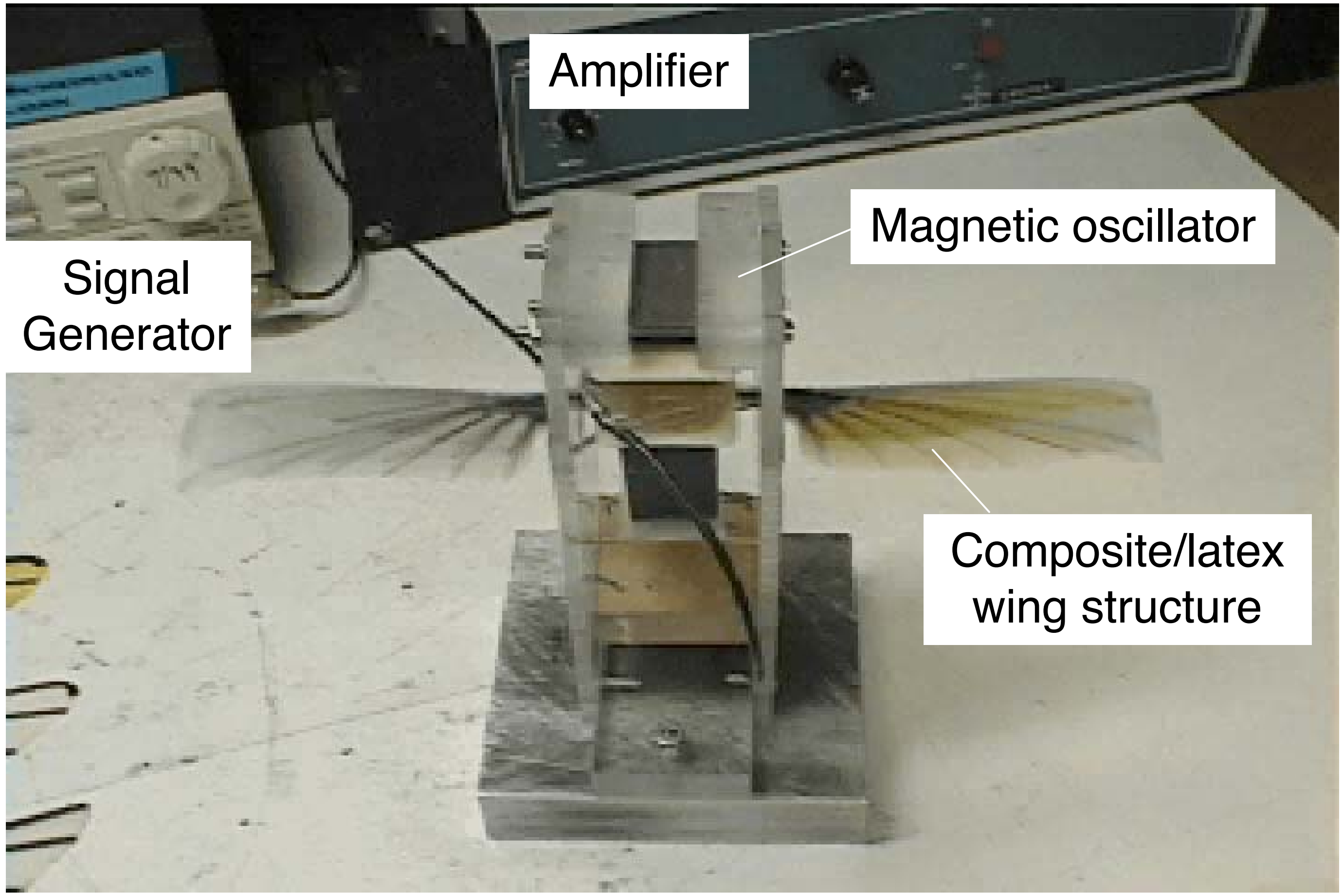




Dual Shakers **('02-'03)**
- Wingtip trajectory traces
- 3-DOF shoulder joint
- Control of wing- beat pattern
- Actuator specs

Magnetically-Actuated Resonant Flapping Testbed used to Excite Aeroelastic Wing Structures

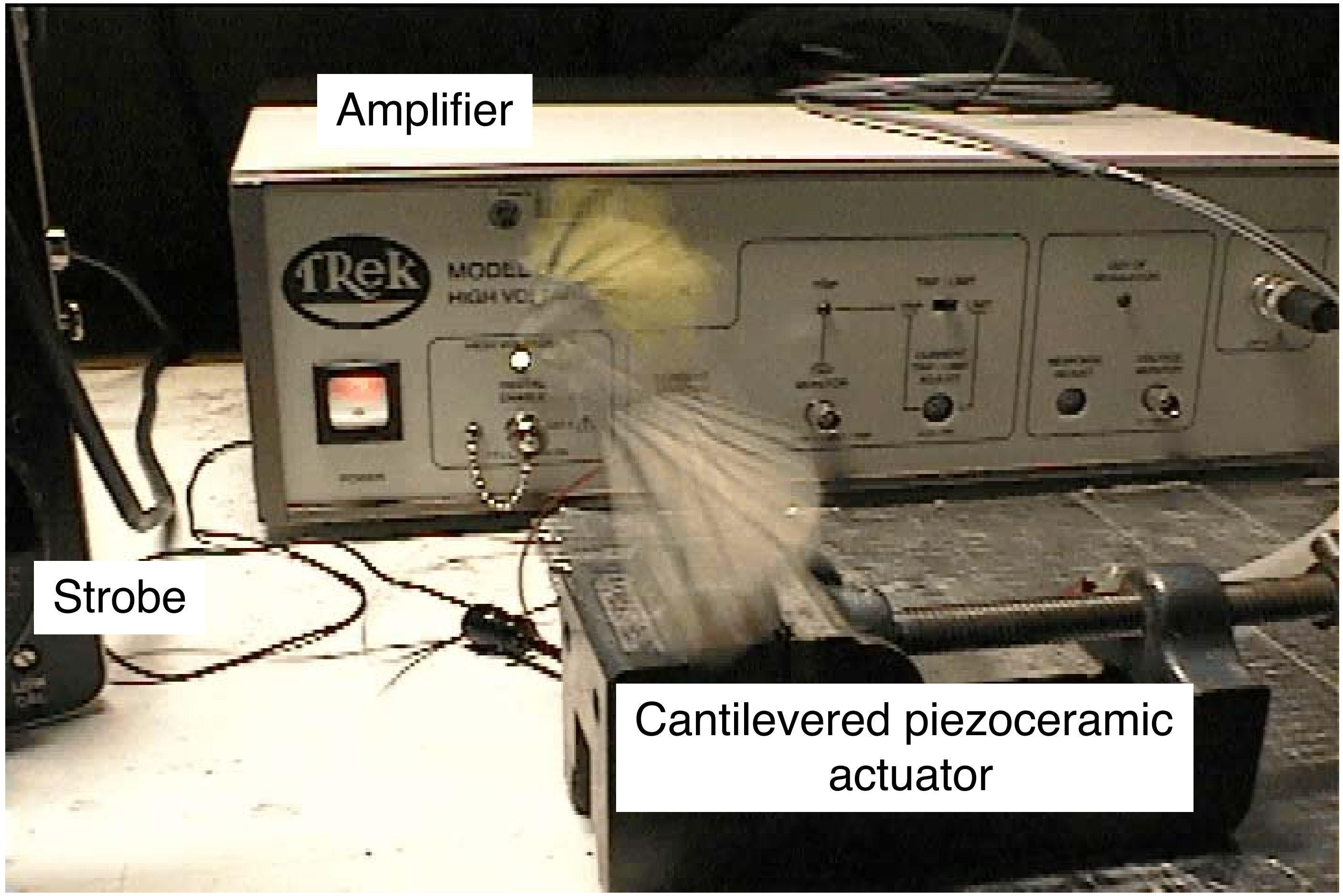
- 0.26gm vs. 0.59gm
- radial battens
- stiffness distribution



- Achieved 20 deg flapping arc at ~ 25 Hz (Relatively low flapping amplitude)
- Resonance coincides with hummingbird flapping frequency for this size
- Kinematics are currently an arbitrary result of cut & try composite layup; Would prefer to specify desired kinematics and solve for required layup
- Generated smoke flow visualization of unsteady aero phenomena

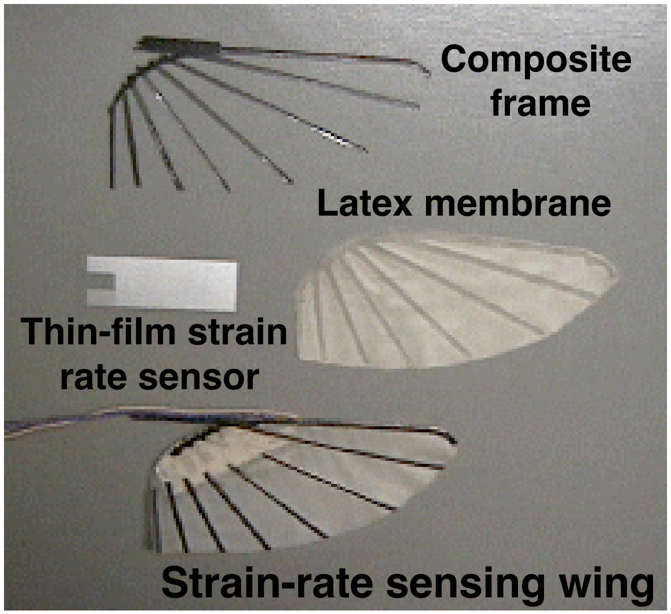
Piezo-Actuated Flapping Testbed

Piezoelectric *thunder* actuator used to excite structural vibration at ~25 Hz

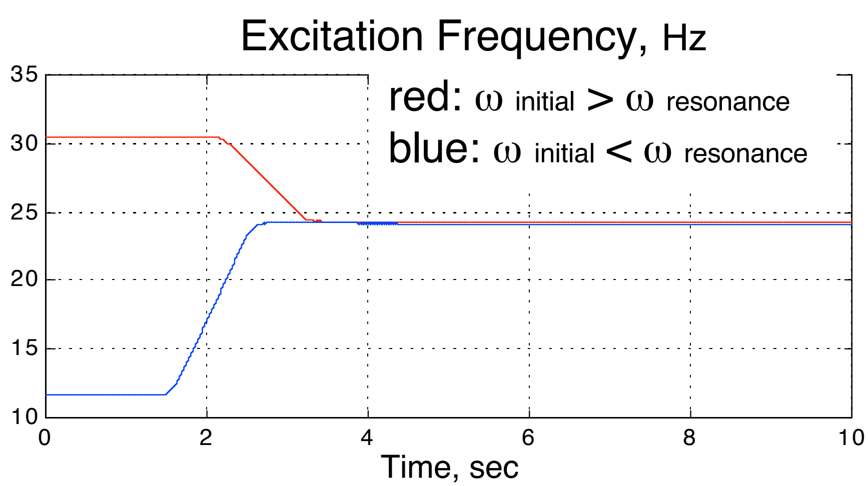


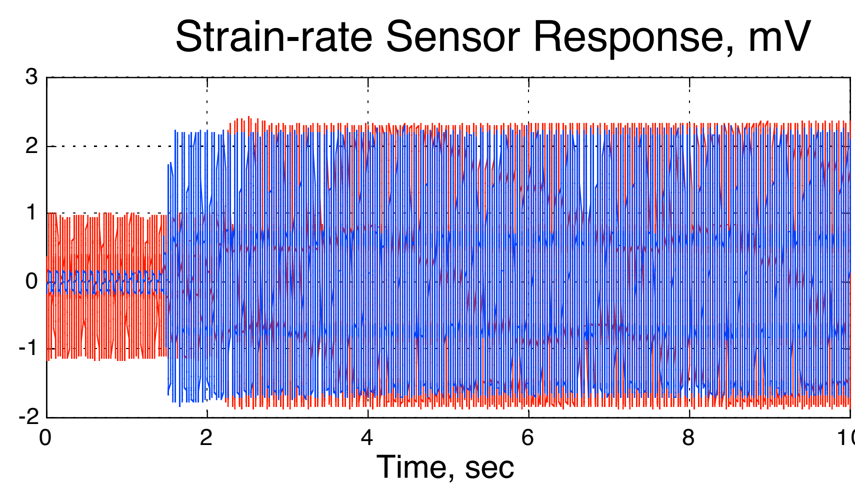
- Much larger amplitude flapping motions achieved with piezo actuation
- Power consumption: 0.46 W; Blue throat in hover: 0.17 W - 0.34 W
- Flow visualization indicates unsteady vortex structures that are suggestive of "vortex capture" phenomenon exploited by insects as postulated by Dickinson, (*Science, vol 284, 18 Jun 99*)

Resonant Tuning using 28 μm PVDF Strain-Rate Sensor



- Bio Inspiration reference: R. Dudley, *Biomechanics of Insect Flight*
- Hardware-in loop feedback controller implemented using *dSpace* system
- Closed loop system exhibits limit cycle at resonant frequency of aeroelastic wing & actuator system

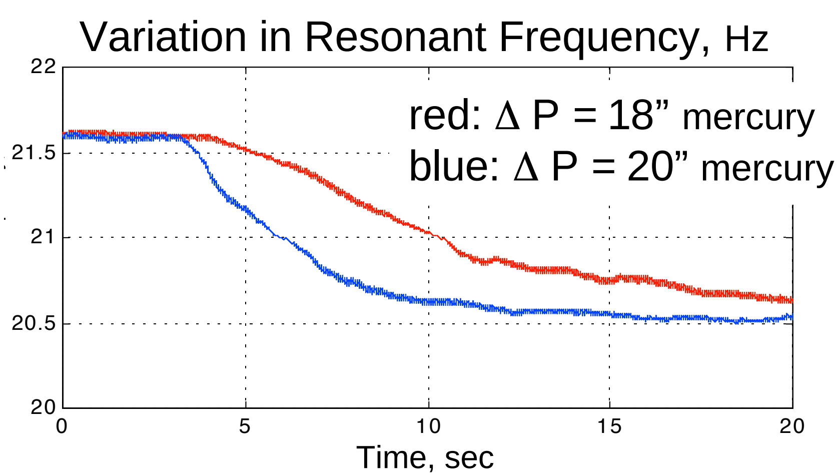


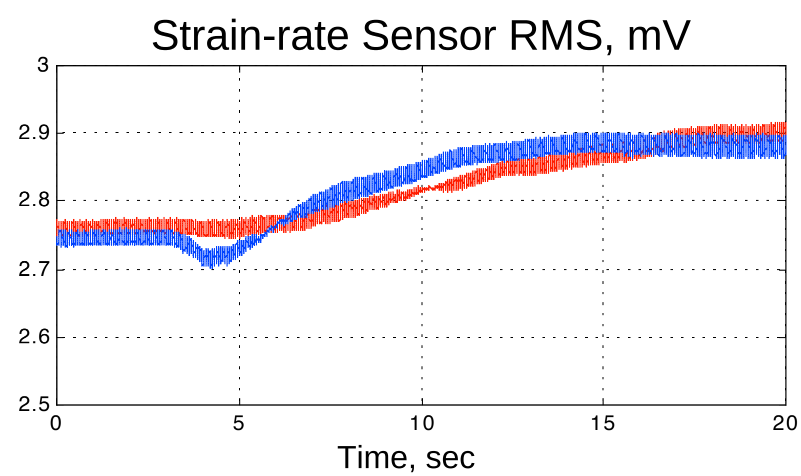


Response of Resonant Flapping System to Ambient Pressure Variation

- Bell jar enables closed-loop structural dynamic testing under time-varying pressure conditions
- Closed-loop system tracks change in modal frequency with pressure variation
- Change in resonant frequency is approximately 1.1Hz for 20” mercury

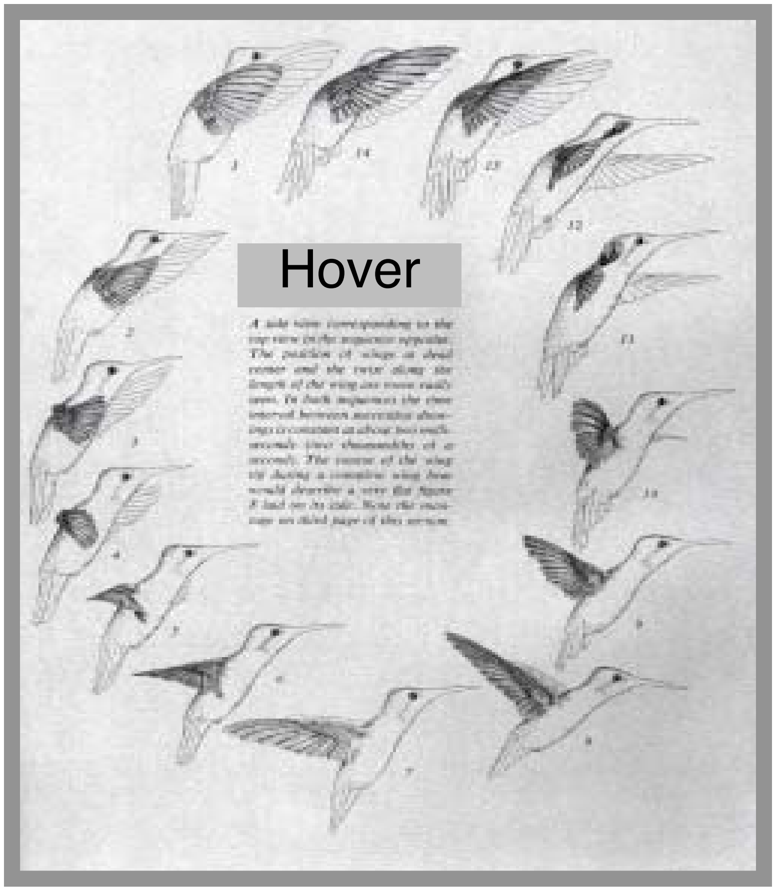
Resonance tracking using 28 μm PVDF thin-film sensor with flexible wing

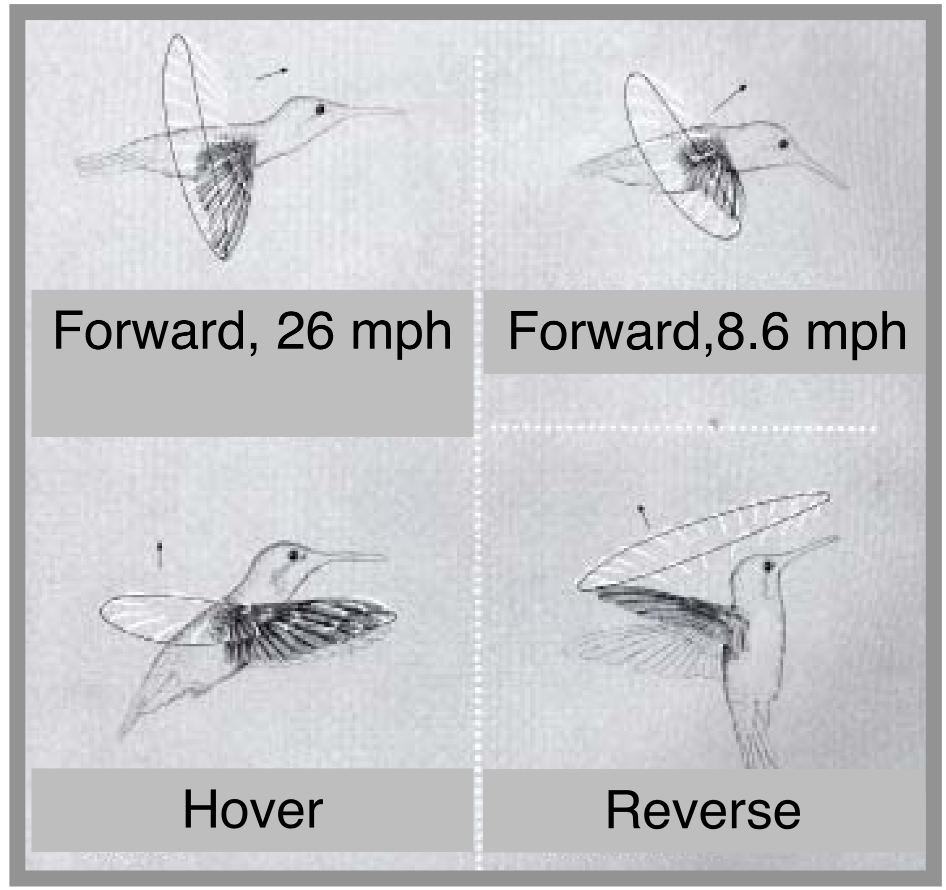




Variable Wingbeat Patterns for Agile Flight

ref: Greenwalt, 1960

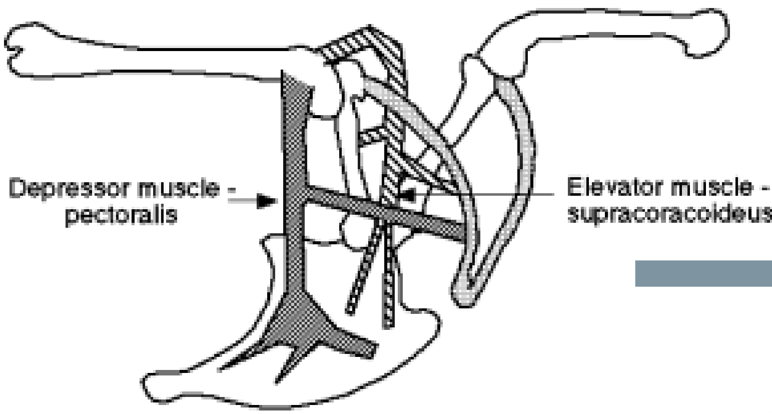


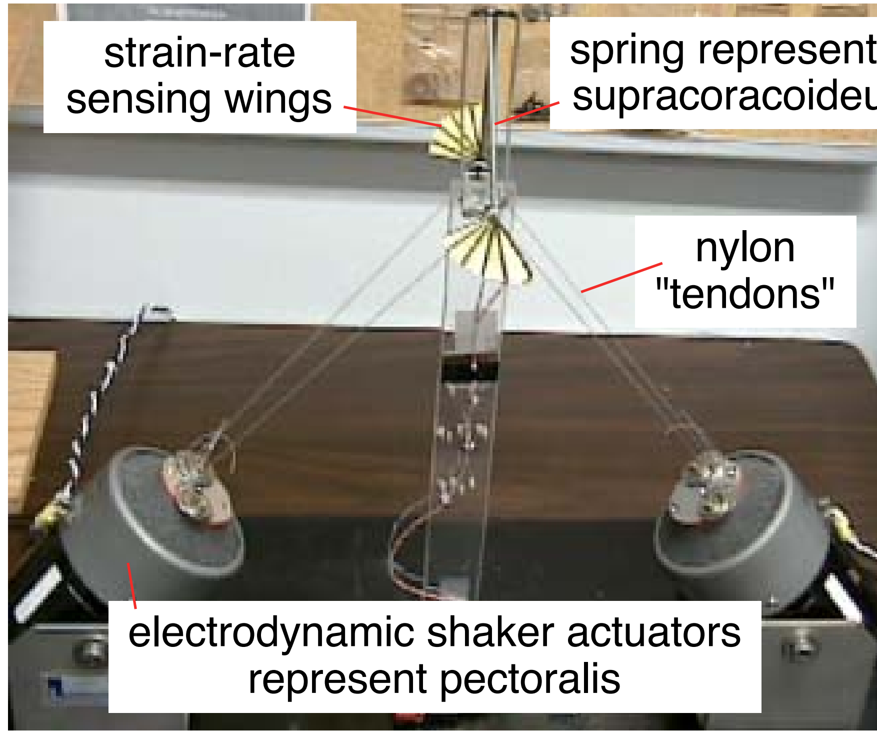


Agility and precision are achieved through coordinated control of resonant wingbeat kinematics and tail effector deployments; flight dynamics and flapping dynamics highly coupled

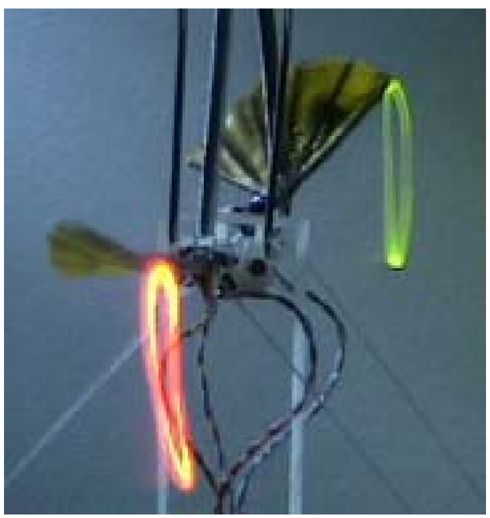
Shaker-Actuated Vibratory Flapping Testbed

Biological Inspiration*



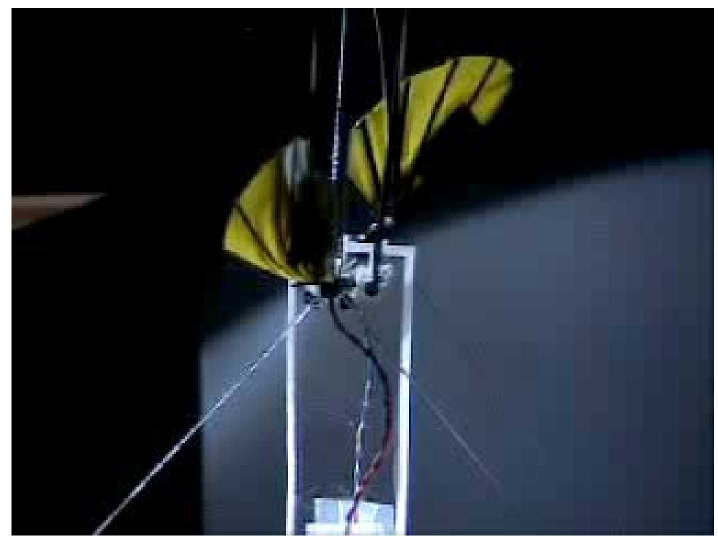


3-DOF shoulder joint permits large amplitude flapping arc & control of wingbeat pattern



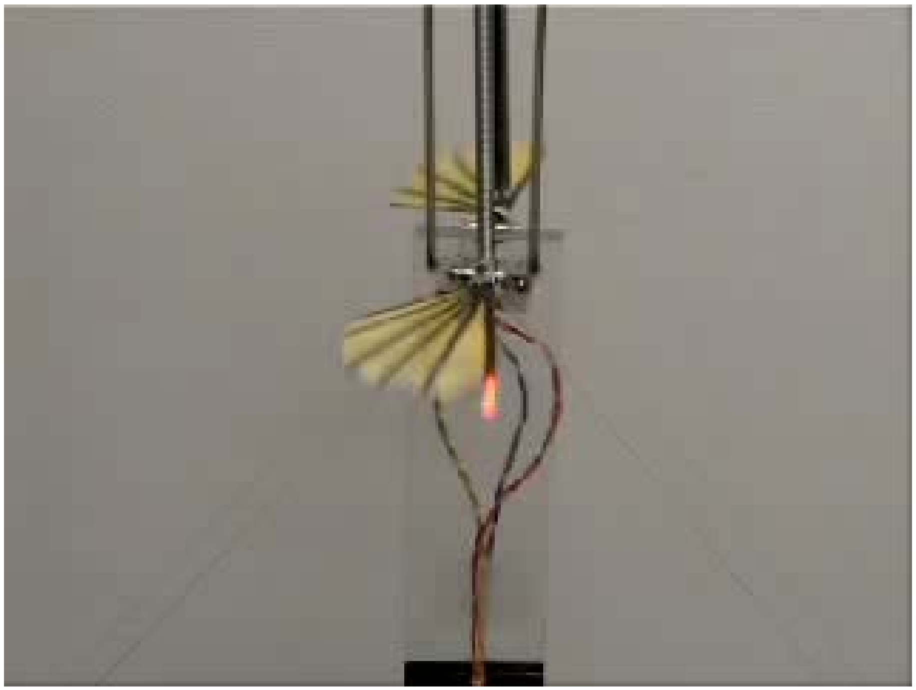
LEDs trace out wingtip trajectory

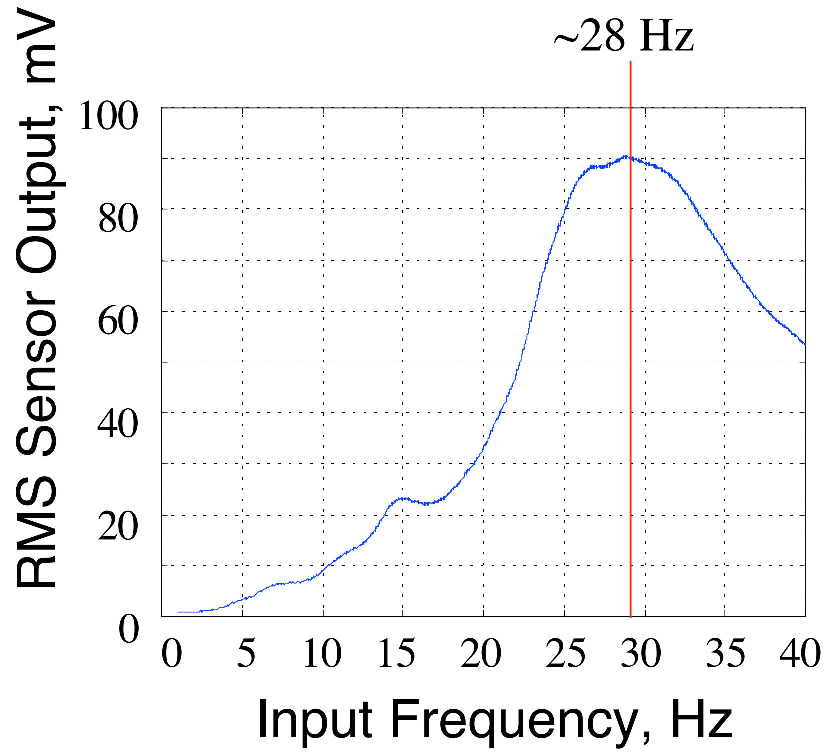
Strobe reveals flexible wing behavior >> Application of resonant tuning circuit



* Cummins J.: Notes on Avian Anatomy webpage, April 1 1996, resketched from Freethy R., 1982: How Birds Work, A Guide to Bird Biology. 1st ed. Poole: Blanford Press. (http://numbat.murdoch.edu.au/Anatomy/avian/shoulderl.GIF)

Open-Loop Sinusoidal Input Frequency Sweeps Reveal Resonant Flapping Frequency

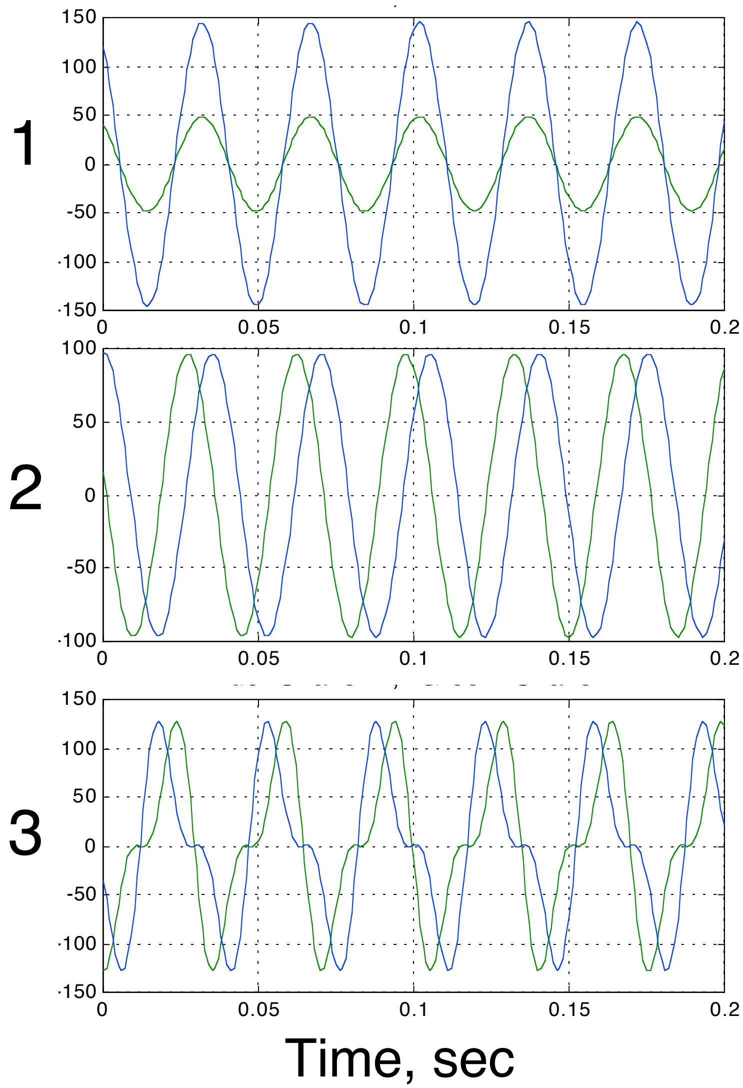




- Output of strain rate sensor is maximized at resonance
- Closed-loop system automatically tunes to this frequency
- Feedback signal can be modified to alter wingtip trajectory

Means of Varying the Wingbeat Pattern

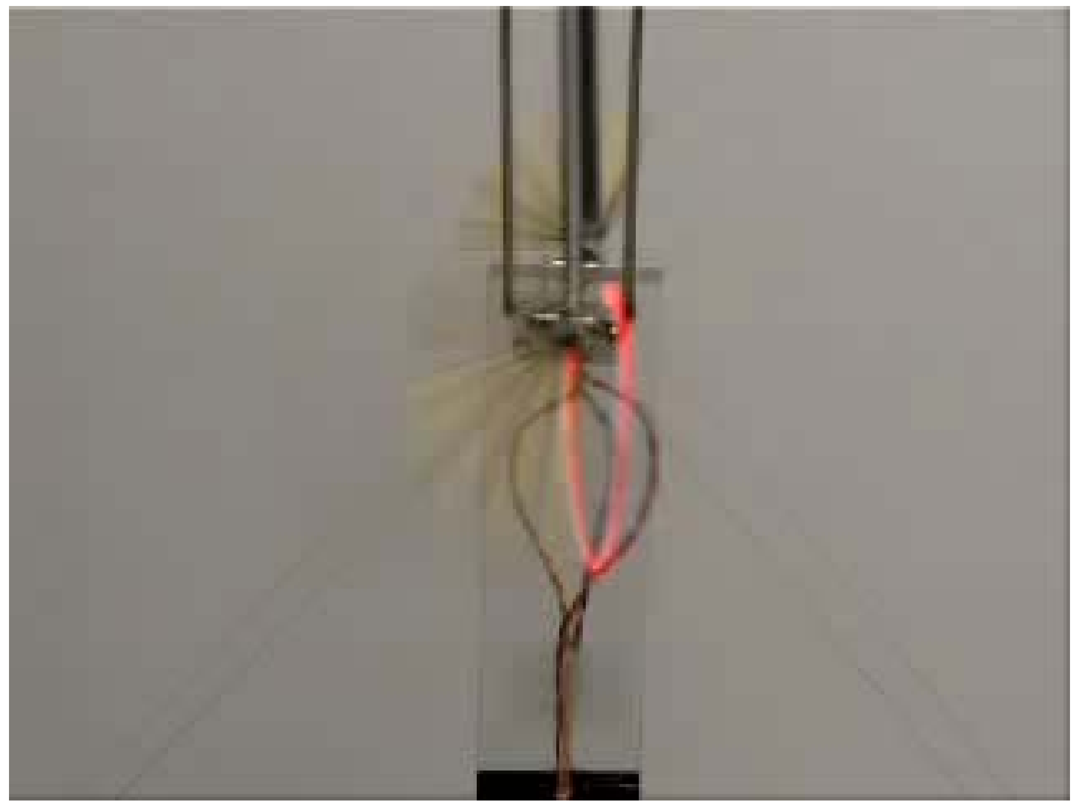
Example Actuator Inputs, mV
Blue=Shaker A, Green=Shaker B



1 Stroke Inclination: vary relative amplitude

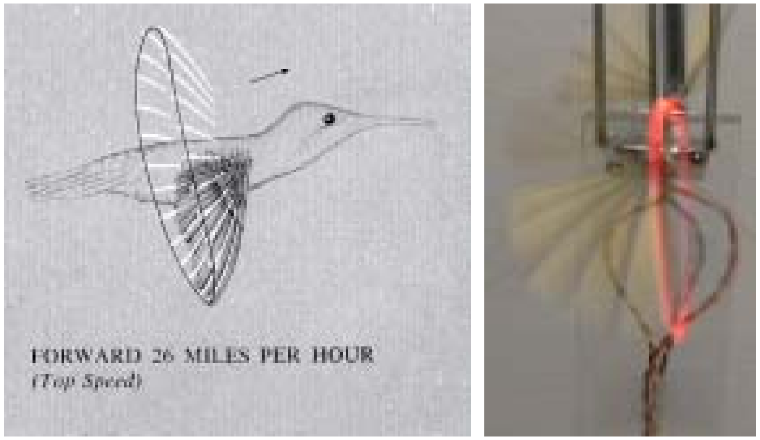
2 Ellipse: vary relative phasing

3 Figure 8: superimpose 2nd sinusoid @ 2 x freq. of fundamental resonance

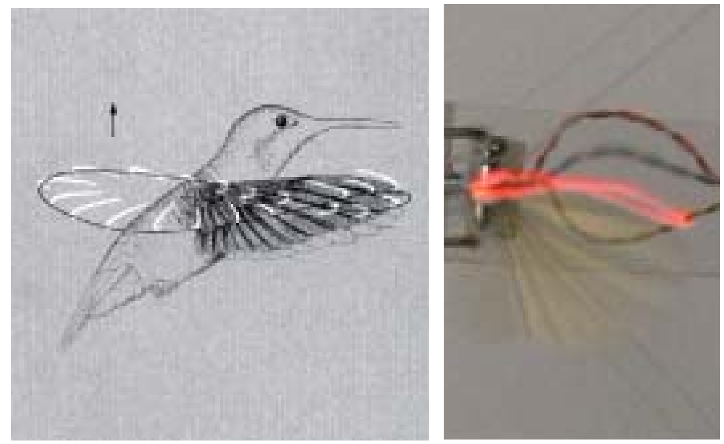


Wingbeat Patterns for Various Flight Modes

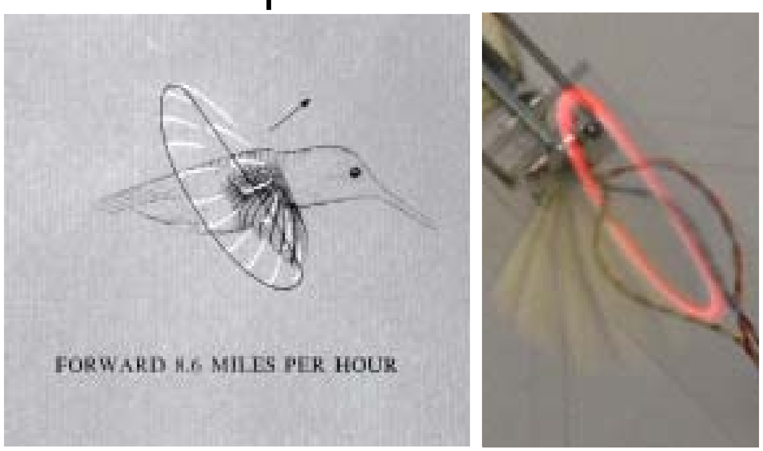
High-Speed Cruise



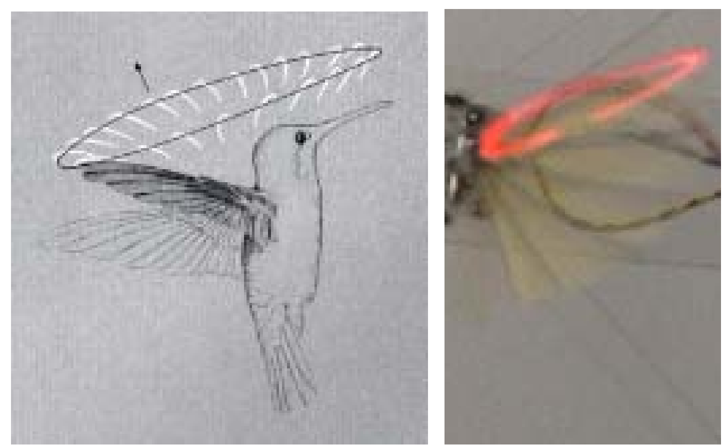
Hover



Low-Speed Cruise



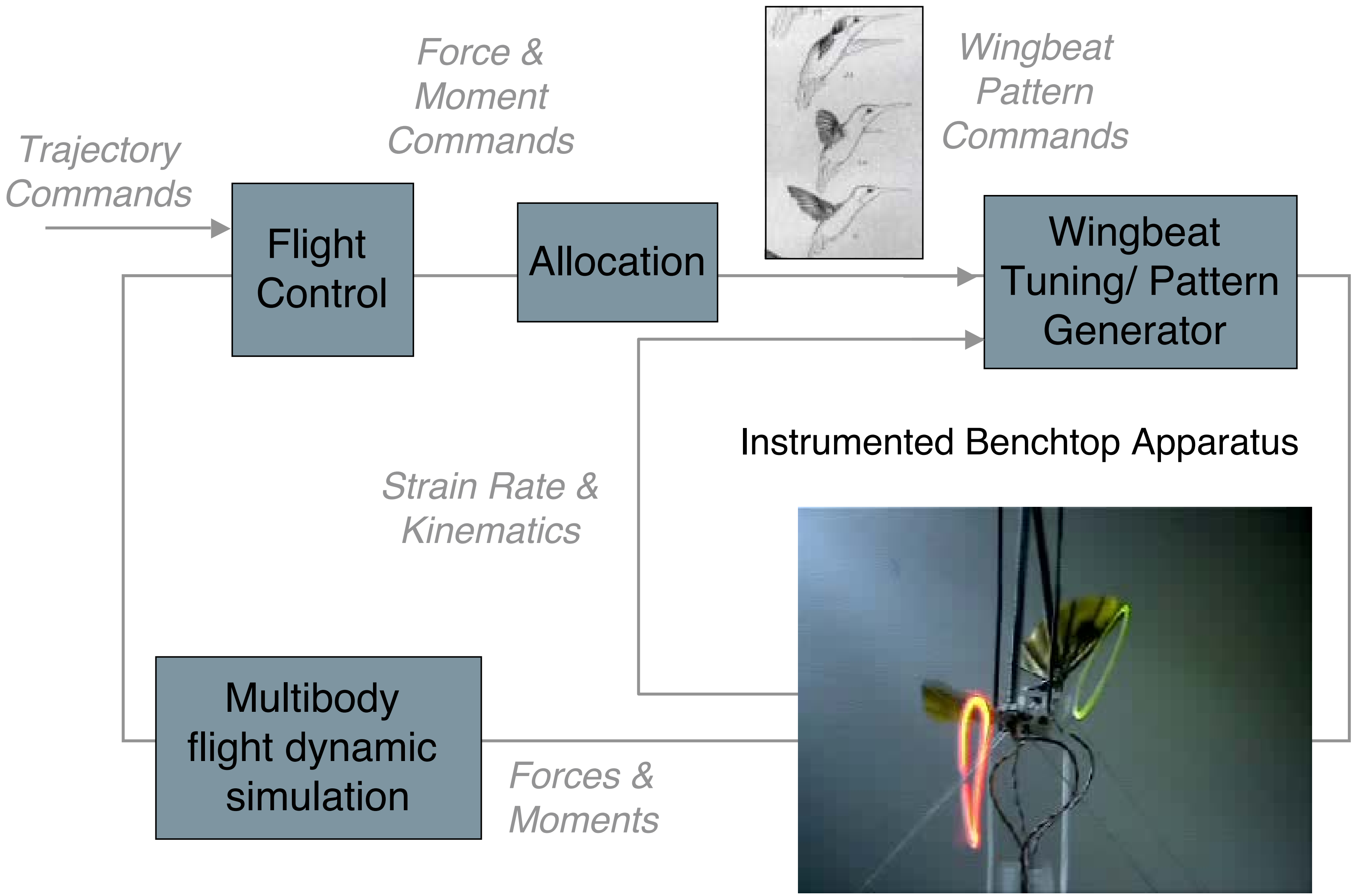
Reverse



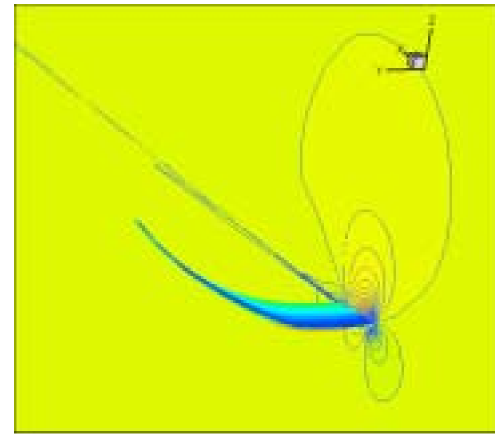
Factors to match

- Wingbeat amplitude
- Strokeplane inclination to body axis
- Approximate wingtip trajectory
- Sense of rotation

Towards Hardware-in-Loop Flight Dynamic Simulation of an Agile Ornithoptic MAV



Other Contacts & Collaborations

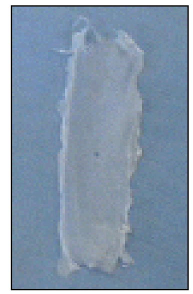


Aeroelasticity Branch (SMC) - R. Lake

- Inverse Aeroelastic Design

Advanced Materials Branch (SMC) - K. Pawlowski

- Electrostrictive Polymer Actuators

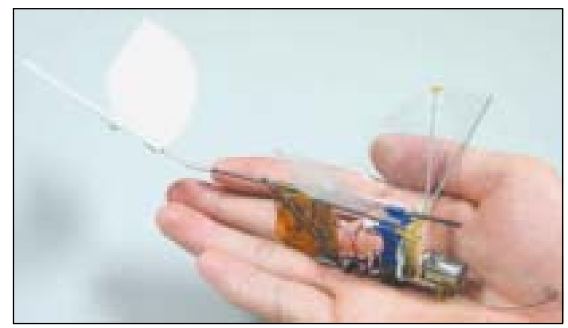


Config. Aero Branch (AAAC) - P. Pao

- Unsteady Aero

Aerovironment - J. Grasmeyer

- “Wasp”, “Black Widow”, “Microbat”



UC Berkeley - R. Dudley

- Dept Int. Biology & “MFI” lab

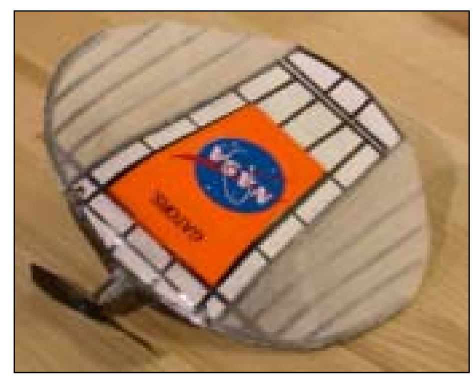
USC - G. Spedding

Duke - N. Chokani & **U. Colorado** - K. Park

- LARSS students & LaRC vibratory apparatus

8th International MAV Competition

U of Arizona/ Brigham Young University/ Cal Tech/ U of Florida/
GA Tech/ Aachen University, Germany**/ Konkuk University**, S. Korea**, …**



Questions?